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An automated computational tool for drilling quality assurance and quality control in block caving mining

Juan Pablo Henríquez [a,*] , Carlos Torres [a], Danko Morales [a]

[a] *Enaex, Chile*

Abstract

Drilling quality control is a key factor in the performance of blasting and cave development in block caving operations. However, quality assurance and quality control (QA/QC) analysis of drilling data is often manual, time-consuming, and inconsistent – particularly when large datasets and multiple excavation stages are involved.

This paper presents a computational tool, developed by Enaex's underground team, for automated QA/QC analysis of drilling in block caving mines. The tool integrates real drilling data obtained from drilling rigs or borehole deviation measurement instruments and automatically compares them with the theoretical blast design using vector projection analysis. Key parameters such as inclination, bearing, collar position, hole length, and spatial deviation are evaluated.

The system automatically generates graphical outputs and summary tables, including traffic-light alert indicators based on predefined tolerance criteria. In addition to drilling data, the tool allows the incorporation of pre-blast information, such as hole cleaning length and post-blast data – including actual explosive loading lengths.

A distinctive capability of the tool is the extrapolation and triangulation of drilling data to generate three-dimensional solids and volumes representing the effective blast geometry. This enables advanced pre- and post-blast analyses, such as verifying connectivity between undercut levels and drawbell, or identifying potential remnant pillars between parallel drifts in the undercut level due to undercut blasts.

All analyses are performed automatically, significantly reducing processing time while improving consistency, engineering quality, and decision-making efficiency in block caving drilling QA/QC workflows.

Keywords: *block caving, QA/QC, borehole deviation, blast design, 3D geometry*

1 Introduction

The success of block caving operations relies heavily on the precise execution of drilling and blasting to ensure effective cave propagation, fragmentation, and drawpoint availability. As mining depths increase and geomechanical conditions become more challenging, the tolerance for drilling errors decreases. Inaccurate drilling can lead to significant operational issues, including hang-ups, poor fragmentation, damage to pillars, and incomplete undercut connectivity (Morales & Olivares 2014; Paredes et al. 2019).

Drillhole deviation is an inherent challenge in deep underground mining. Recent studies on drawbell construction have shown that deviation is not random but influenced by factors such as hole inclination and depth. For instance, Bustos et al. (2020) analysed over 2,000 holes in block caving and found that holes with lower inclination (corner rings) exhibit higher deviation, potentially exposing pillars to blast damage or leaving remnant rock.

[*] Corresponding author. Email address: juanpablo.henriquez@enaex.com

Despite the critical nature of drilling accuracy, quality assurance and quality control (QA/QC) processes in many operations remain manual, labour-intensive, and prone to human error. Engineers often face the challenge of processing massive datasets from multiple rigs and deviation measurement probes (e.g. gyroscopes) under tight time constraints. This manual approach often leads to inconsistent analysis and delayed decision-making, where deviations are detected only after loading or, worse, after blasting (Henriquez et al. 2024).

To address these challenges, the industry requires automated solutions capable of processing large volumes of drilling data in near real-time. This paper presents an automated computational tool designed specifically for block caving environments. The tool systematises the QA/QC workflow by integrating real drilling data, performing automated vector-based comparisons against theoretical designs, and generating 3D volumetric models of the 'as-drilled' geometry. This approach enables engineers to visualise effective blast geometries, verify undercut-drawbell connectivity, and identify potential remnant pillars before explosive loading, thereby shifting the focus from reactive to proactive blast control.

2 Methodology

The developed computational tool is based on the comprehensive QA/QC methodology for drilling and blasting cycles in underground mining (Henriquez et al. 2024). The workflow is divided into 3 main stages: data integration, automated vector analysis, and 3D volumetric modelling.

2.1 Data integration and pre-processing

The system is designed to ingest data from various sources common in block caving operations.

- Theoretical design: input of the designed blast patterns (x, y, z coordinates of collar and toe, azimuth, dip, and length) for drawbells, undercut rings, or radial drilling.
- Actual drilling data: import of 'as-drilled' data obtained from drilling rig logs or, more accurately, from borehole deviation measurement instruments (e.g. Reflex).
- Operational constraints: definition of specific tolerances for the mine sector (e.g. maximum allowable toe deviation, collar error, or angular difference).

2.2 Automated vector comparison

Once the data is imported, the tool performs an automated comparison between the theoretical vector and the actual vector for every hole in the pattern. The algorithm calculates:

1. Collar deviation: Euclidean distance between designed and actual collar coordinates (Figure 1).
2. Angular deviation: difference in azimuth and inclination (dip).
3. Toe/spatial deviation: the vector difference at the target depth, critical for ensuring toe spacing and burden.
4. Length discrepancy: comparison of designed versus drilled length to identify short holes (potential underbreak) or over-drilled holes (potential damage to surrounding infrastructure).

The system applies a 'traffic-light' protocol (green/yellow/red) based on the predefined tolerances, instantly flagging holes that require re-drilling or specific loading instructions.

Figure 1 Vector comparison: the real drillhole in grey, the vector projection in lines

2.3 Three-dimensional solid generation and connectivity analysis

A distinctive capability of the tool is the generation of 3D solids. Instead of analysing holes as single lines, the tool extrapolates the influence volume of each hole based on the actual drilling data.

- Effective blast geometry: by triangulating the ‘as-drilled’ toes and collars, the tool generates a solid representing the rock mass that will be fractured.
- Connectivity verification: in block caving, connecting the undercut level with the drawbell is critical. The tool superimposes the generated undercut solids with the drawbell solids to verify overlap. Gaps in this overlap indicate potential ‘remnant pillars’ or ‘stumps’ that could inhibit caving initiation.
- Remnant pillar identification: similarly, for parallel drifts in the undercut, the tool analyses the interaction between adjacent fans to ensure no solid ground remains between them due to divergent drilling.

2.4 Post-blast data integration

Finally, the tool allows the incorporation of post-process data, such as hole cleaning lengths and actual explosive loading lengths (obtained from smart loading equipment such as Enaex UBEX/UBS). This enables a complete reconciliation between the ‘drilled geometry’ and the ‘charged geometry’, providing the final inputs for energy distribution analysis.

3 Methodology

The computational tool has been applied across various scenarios representing common drilling challenges and workflows in large-scale block caving operations. These applications demonstrate the tool's capabilities in streamlining QA/QC processes, enhancing decision-making, and providing advanced analytical insights.

3.1 Comprehensive data integration and visualisation

The tool successfully integrates ‘as-drilled’ data from diverse sources, including output files from borehole deviation measurement instruments (e.g. Reflex gyroscopes) and logs from modern drilling rigs. This functionality facilitates the rapid upload and comprehensive processing of entire drilling campaigns, comprising thousands of drillholes. An intuitive 3D visualisation module allows engineers to view the as-drilled patterns for drawbells and undercut radial patterns, providing a holistic understanding of the drilling geometry across the mine. Concurrently, theoretical blast designs can be uploaded with ease, establishing an immediate and accurate baseline for comparison (Figure 2).

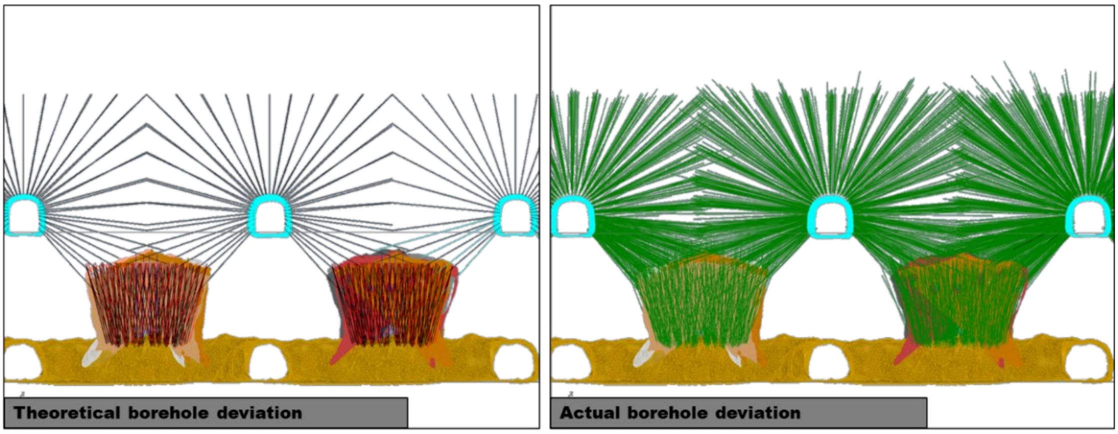


Figure 2 3D block caving drilling (theoretical and actual)

3.2 Automated comparative analysis and alert system

A core application of the tool is the automated comparison between the theoretical and as-drilled geometries. Utilising predefined and user-customisable acceptance ranges, the system autonomously evaluates critical drilling parameters, including burden, spacing, inclination, hole length, and collar deviation. The results are instantly presented through dynamically generated graphs, summary tables and 3D visualisations (Figures 3 and 4), which feature a clear traffic-light alert system (green, yellow, red indicators). This rapid and consistent feedback mechanism allows operational and engineering teams to promptly identify non-conformances and prioritise corrective actions, significantly reducing the manual effort associated with traditional QA/QC.

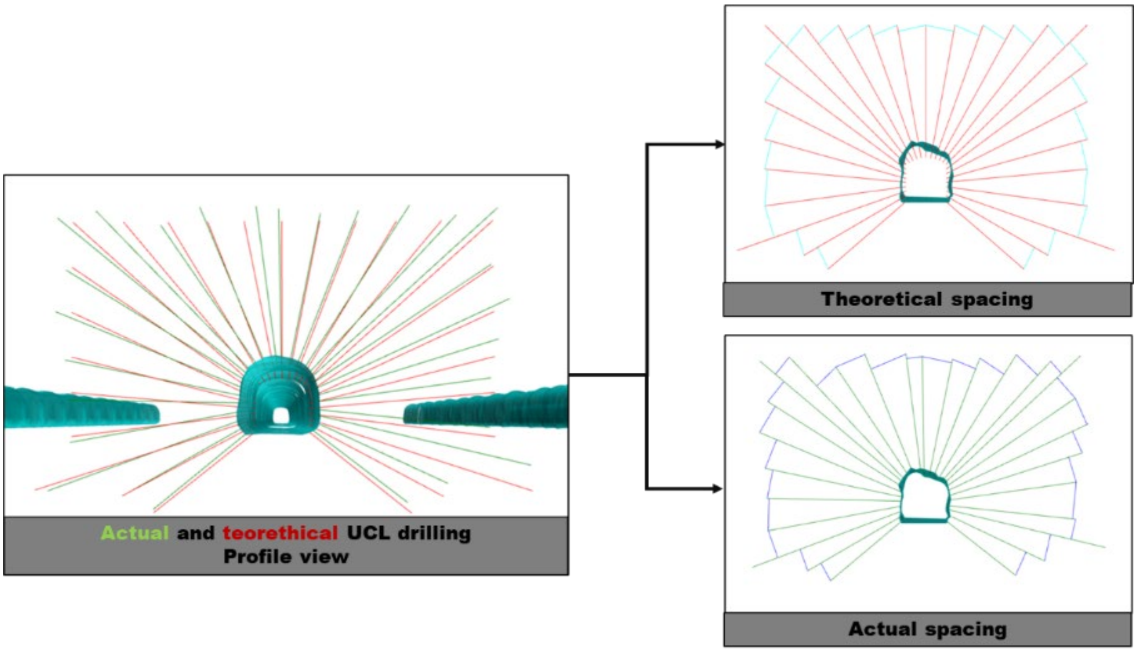
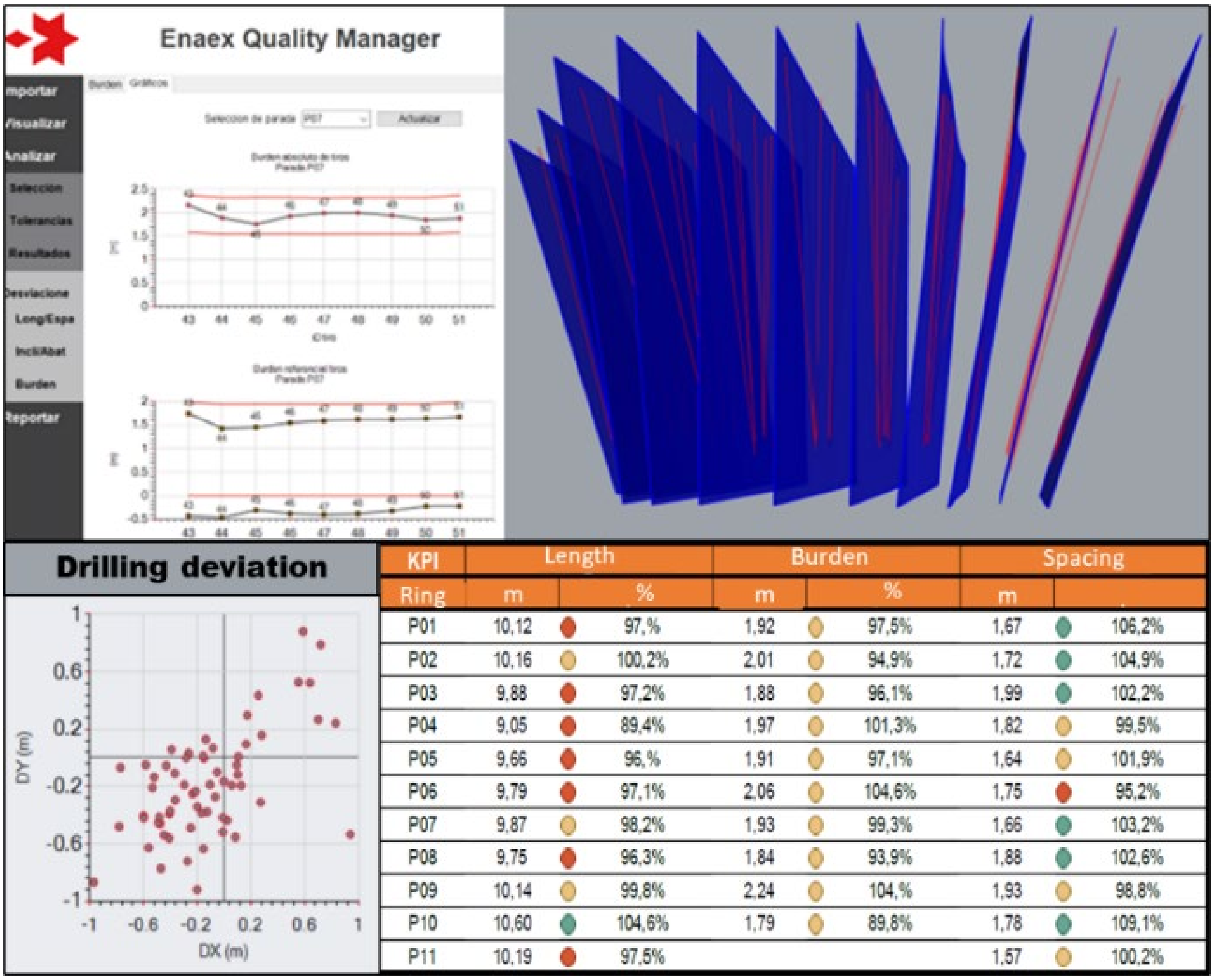


Figure 3 Undercut level (UCL) borehole spacing (theoretical and actual)



KPI / Ring	Length m	Length %	Burden m	Burden %	Spacing m	Spacing %
P01	10,12	97,%	1,92	97,5%	1,67	106,2%
P02	10,16	100,2%	2,01	94,9%	1,72	104,9%
P03	9,88	97,2%	1,88	96,1%	1,99	102,2%
P04	9,05	89,4%	1,97	101,3%	1,82	99,5%
P05	9,66	96,%	1,91	97,1%	1,64	101,9%
P06	9,79	97,1%	2,06	104,6%	1,75	95,2%
P07	9,87	98,2%	1,93	99,3%	1,66	103,2%
P08	9,75	96,3%	1,84	93,9%	1,88	102,6%
P09	10,14	99,8%	2,24	104,%	1,93	98,8%
P10	10,60	104,6%	1,79	89,8%	1,78	109,1%
P11	10,19	97,5%			1,57	100,2%

Figure 4 Analysis summary

3.3 Advanced volumetric and connectivity analysis

A distinctive capability demonstrated by the tool is the projection of drilling data into 3D solids. These solids represent the effective blast geometry, both as-designed and as-drilled. This volumetric analysis supports advanced pre-blast assessments, such as verifying the connectivity between undercut levels and drawbell formations, as shown in Figure 5. By comparing the 'as-drilled' solids of adjacent blasts, the tool can identify potential remnant pillars or areas of insufficient rock fragmentation due to divergent drilling (Figure 6), a critical function for maintaining cave integrity and minimising dilution.

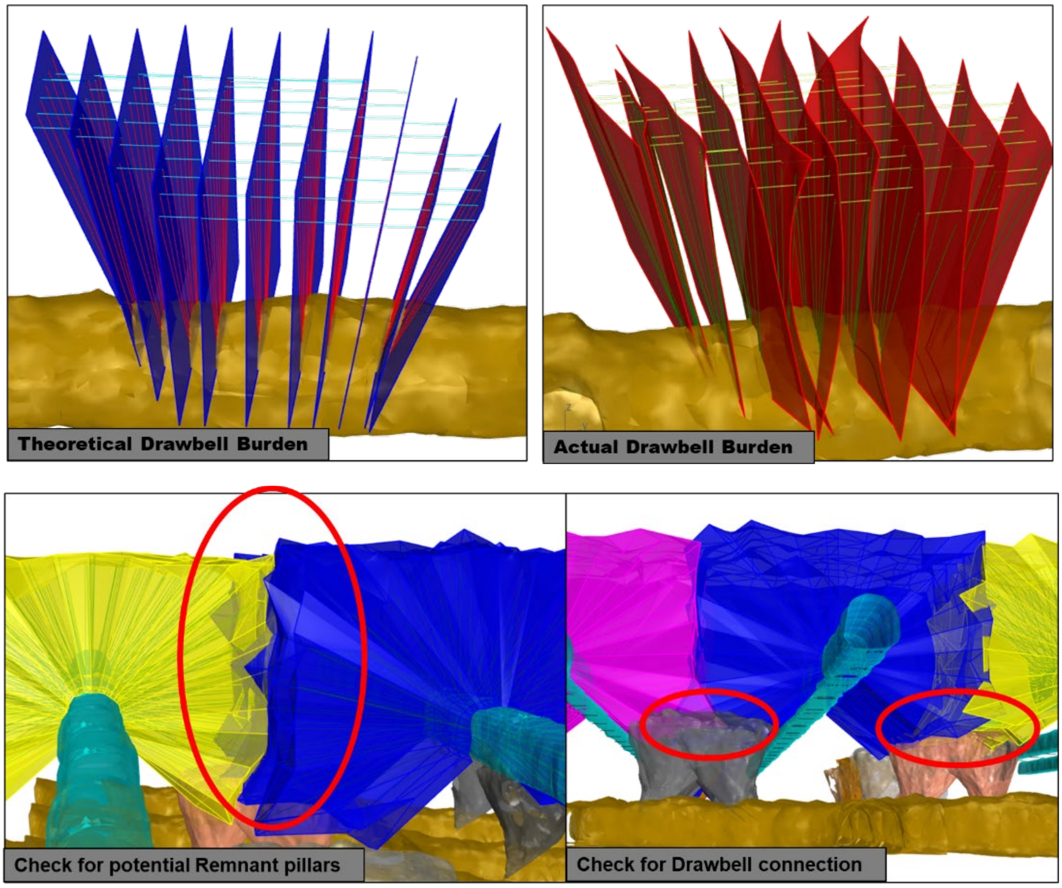


Figure 5 Burden visualisation, remnant pillars and drawbell connection check

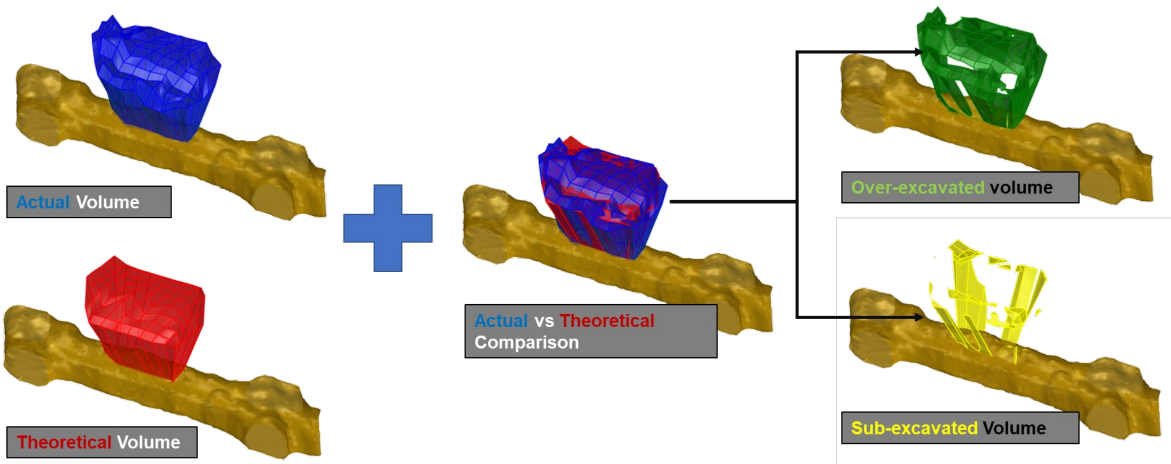


Figure 6 Comparison of theoretical and actual volumes

3.4 Integrated blast design optimisation

When the drilling QA/QC results meet the defined acceptance criteria, the tool seamlessly transitions to support the explosive loading design. This module assists in generating optimal loading proposals, including the precise positioning of primers, calculation of explosive quantities per hole, and definition of initiation sequences (Figure 7). This ensures that the blast design is not only based on theoretical parameters but is also adapted to the actual, measured drilling conditions, thereby maximising blast effectiveness and safety.

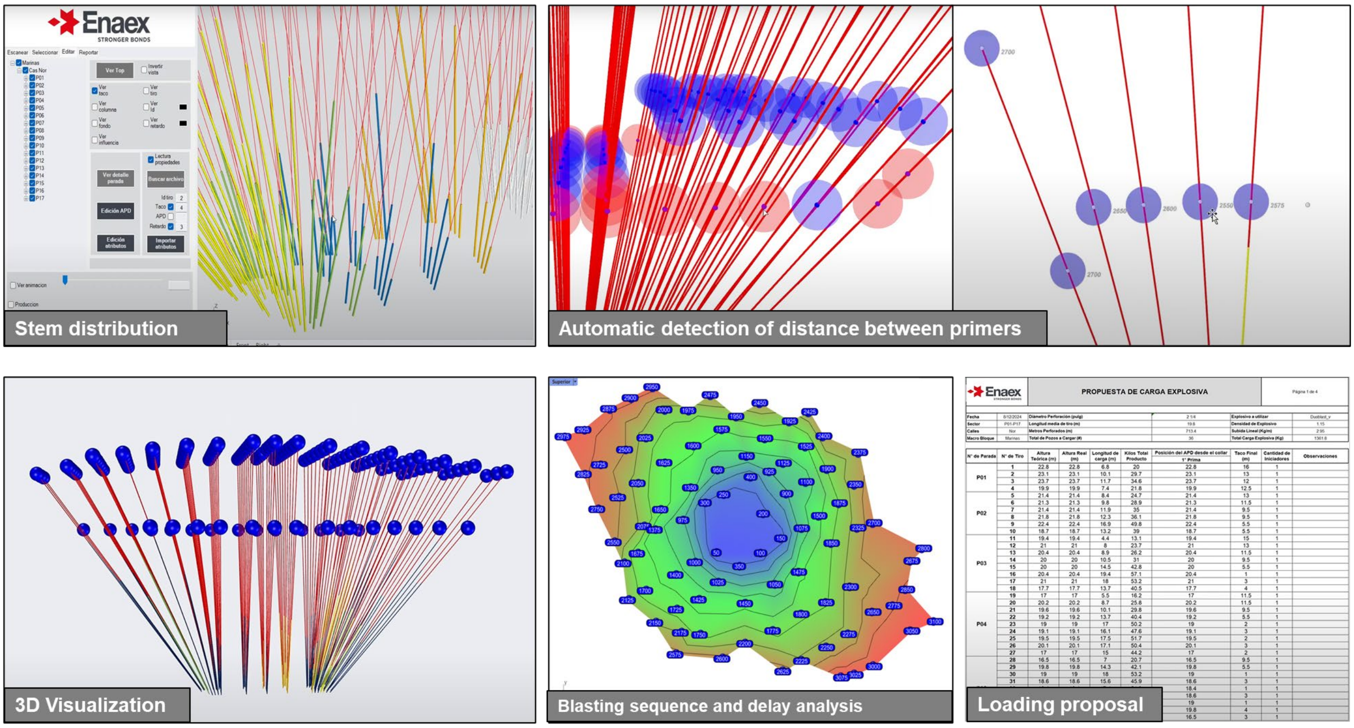


Figure 7 Blast design optimisation module

3.5 Data export and cloud-based management

The tool enables the export of processed and reconciled drilling and explosive loading datasets in formats compatible with external blast simulation software. This ensures that any subsequent numerical modelling or analysis is based on the most accurate information available. All generated data, analyses, and reports are securely stored in a cloud-based environment, guaranteeing data integrity, providing an audit trail, and supporting collaborative workflows and continuous improvement initiatives across multiple operational units.

4 Conclusion

This paper introduces an automated computational tool developed by Enaex's underground team, specifically designed to enhance drilling QA/QC in block caving operations. Through its integrated three-stage methodology encompassing design, execution, and post-blasting analysis, the tool delivers significant advancements over traditional manual processes.

The primary conclusions drawn from this study are as follows:

1. Streamlined and consistent QA/QC: the tool automates the entire QA/QC workflow, from integrating actual drilling data from diverse sources (e.g. Reflex probes) to performing vector-based comparisons against theoretical designs. This automation dramatically reduces the time previously consumed by manual analyses, ensuring consistent and objective evaluation of drilling accuracy across extensive datasets.

2. Enhanced decision-making and risk mitigation: by providing automated alerts (traffic-light indicators) and immediate graphical feedback on critical parameters (burden, spacing, inclination, length, collar deviation), the tool empowers engineering and operational teams to make timely, data-driven decisions. This proactive approach facilitates early identification of potential issues, such as excessive deviation in critical areas (e.g. drawbell shoulders), which could lead to poor fragmentation, incomplete cave propagation, or undesired remnant pillars.

3. Advanced 3D volumetric analysis: a key capability demonstrated is the generation of 3D solids representing the 'as-drilled' geometry. This volumetric analysis enables advanced pre-blast assessments, including the evaluation of effective connectivity between undercut levels and drawbells, and identifying potential remnant pillars within the undercut. Such insights are crucial for maintaining the structural integrity of the mine and optimising the transfer of caved material.
4. Optimised blast design adaptation: the tool seamlessly integrates real drilling data with blast design optimisation. By validating the 'as-drilled' geometry, it ensures that explosive loading proposals, including primer positioning and initiation sequences, are precisely adapted to actual field conditions. This refined design process contributes directly to more effective blasting outcomes, reduced re-work, and improved operational safety.
5. Scalability and data integrity: designed for large-scale block caving environments, the cloud-based data management system guarantees data integrity, traceability, and accessibility. This robust infrastructure supports continuous improvement initiatives and collaborative workflows across multiple mine departments.

In summary, the automated computational tool represents a significant advancement in drilling QA/QC for block caving. By transforming a manual and often inconsistent process into an efficient, data-driven workflow, it provides mining operations with a powerful mechanism to ensure design compliance, optimise blast performance, and enhance the overall predictability and safety of cave development.

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